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Memo

DATE: *January 7, 2005*

TO: RHIC E-Coolers

FROM: *Ady Hershcovitch*

SUBJECT: **Minutes of the January 7, 2005 Meeting**

Present: Peter Cameron, Xiangyun Chang, Alexei Fedotov, Wolfram Fischer, Michael Harrison, Ady Hershcovitch, Jorg Kewisch, Vladimir Litvinenko, Derek Lowenstein, William Mackay, Nikolay Malitsky, Christoph Montag, Thomas Roser, Triveni Srinivasan-Rao, Dejan Trbojevic, Gang Wang (SUNY Stony Brook), Jie Wei.

Topics discussed: Electron Gun Design Review, Experiments at CELSIUS.

Electron Gun Design Review: Vladimir opened the meeting by reporting on the Electron Gun design review at AES, which went well even though the committee's approach was rather conservative. The committee recommended to proceed with the original AES design. But, it noted that the 18-month delivery time was extremely aggressive. Although Vladimir did not think that the committee recommended pursuing the best electron gun, it nevertheless recommended fabricating an electron gun that we can use. Overall the review was very positive, since it continues our forward progress.

Experiments at CELSIUS: Vladimir continued with a description of a series of experiments performed at CELSIUS in Uppsala Sweden last month. Alexei followed Vladimir with a detailed presentation of the experiments and their interpretations. To perform the experiments Alexei and Vladimir were joined by our JINR Dubna (Russia) collaborators Anatoly Sidorin and Alexander Smirnov, as well as by CELSIUS physicists Bjorn Galnader, Tor Lofens, and Volker Ziemann. The main purpose of the study was accurate benchmarking of the cooling force. The experiments determined the following:

1. Longitudinal cooling force was measured accurately (within a few %; far better than the factor 2 goal, or the previously done order of magnitude).
2. Can control V effective and not be sensitive to unknown parameters.
3. The Parkhomchuk model has good agreement with experimental far better than the model of Derbenev, Skrinsky and Meshkov.

This increases confidence in predicting RHIC E-Cooling by using formulas and test whether the VORPAL code yields agreement with experiments.

Vladimir's and Alexei's presentations are below.

Tests of e-Cooling concepts for RHIC at CELSIUS

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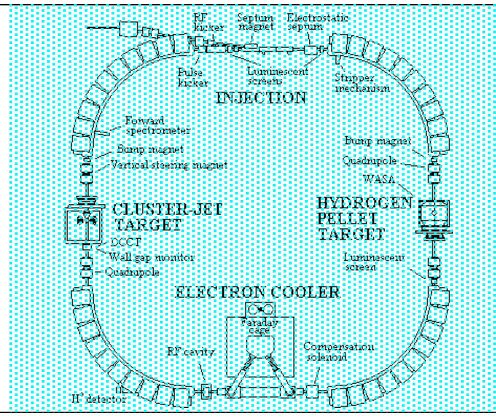
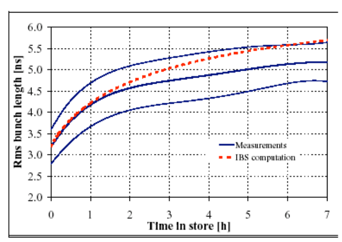
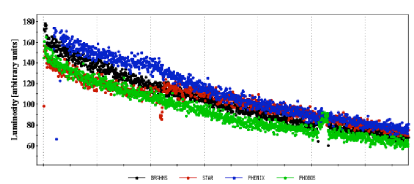


Participants: Björn Gålnander, Tor Lofnes , Volker Ziemann, Alexei Fedotov, Vladimir Litvinenko, Anatoly Sidorin, Alexander Smirnov

Motivation

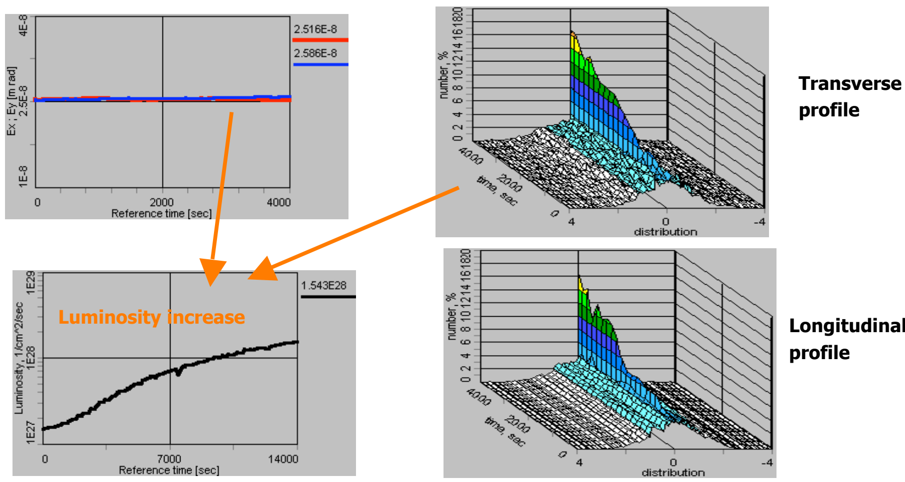
- The motivation for electron cooling of RHIC is to increase luminosity by reducing emittance and overcoming IBS.
  - Increase the integrated luminosity for gold on gold collisions by an order of magnitude, also higher P-P luminosity (RHIC II).
  - Increase the luminosity of protons and ions on electrons and shorten ion bunches (eRHIC)
- Both RHIC II and eRHIC are on the DOE's 20 years facilities plan.





RHIC luminosity decay (3.5 hours)

Cooling gold at 100 GeV/A



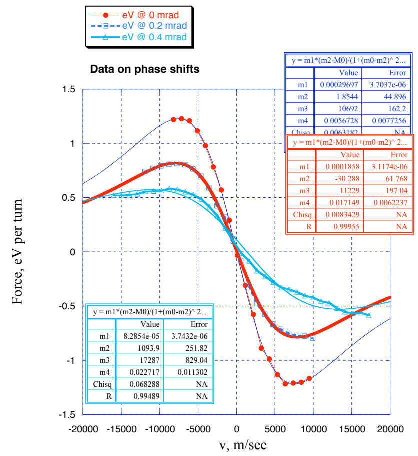
TEST relevant to RHIC e-cooling program

- Key components
  - Accurate (within a factor 2 or better) measurements of the cooling force at low velocities and comparison with theory ✓
  - Test of the influence of misalignment errors ✓
  - Observing formation of core in transverse direction ✓

Vladimir Litvinenko
Uppsala 12/20//04

Accurate measurements of the cooling force using phase shift method

- Key components
  - Accurate phase measurements (Tor)
  - Using the RF frequency for velocity mismatch with the electron beam
  - Using reasonably high RF voltages (~10 V)



TACK!

Looking forward for next visit

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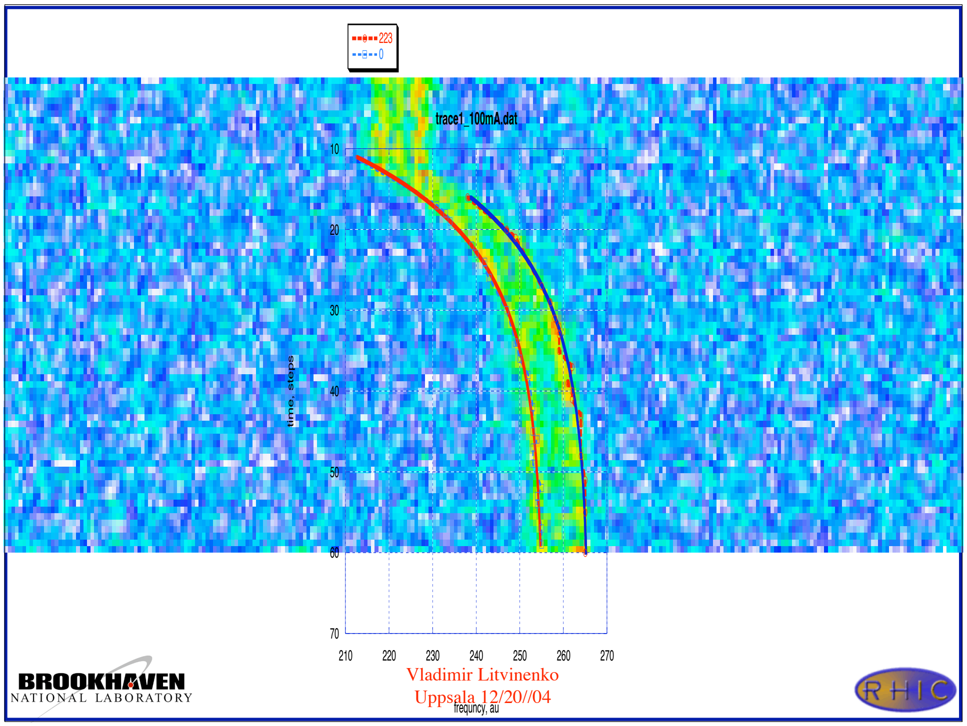
RHIC



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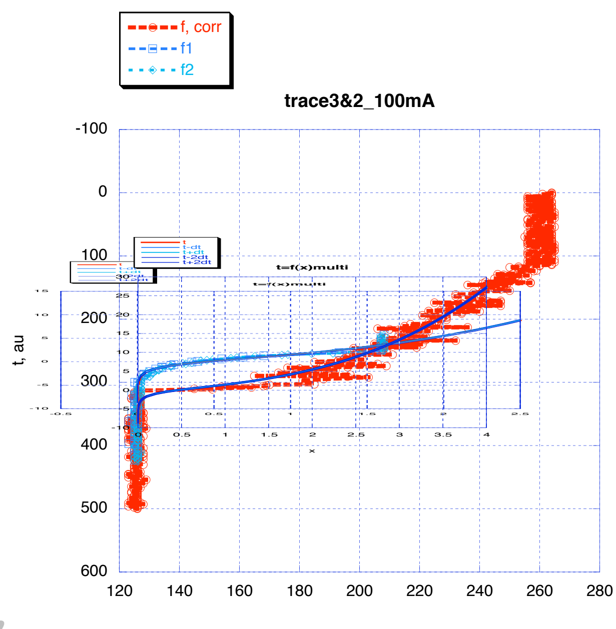
RHIC



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RHIC

Electron Cooling Experiments at CELSIUS

CELSIUS (Uppsala, Sweden), December 13-20, 2004

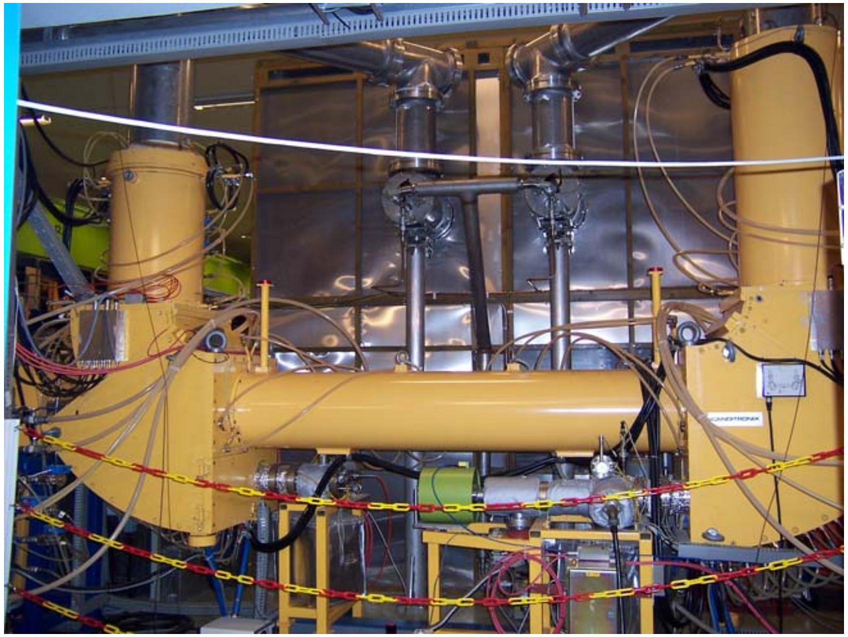
Alexei Fedotov

BROOKHAVEN NATIONAL LABORATORY

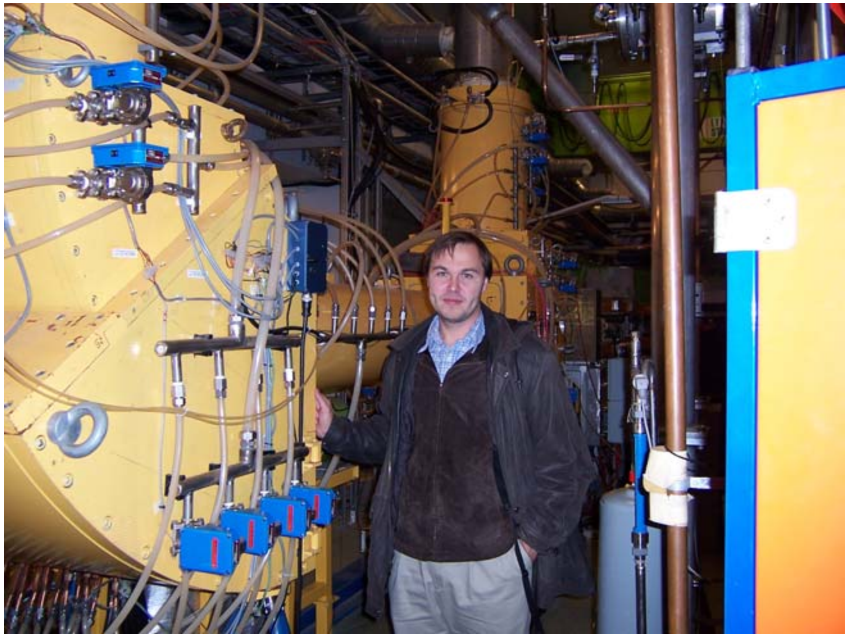
Svedberg Laboratory, Uppsala, Sweden

CELSIUS

Electron Cooler



Team



CELSIUS: **Bjorn Galnader, Tor Lofnes, Volker Ziemann**

BNL: **Alexei Fedotov, Vladimir Litvinenko**

JINR: **Anatoli Sidorin, Alexander Smirnov**

Experiment: ACCURATE benchmarking of cooling force

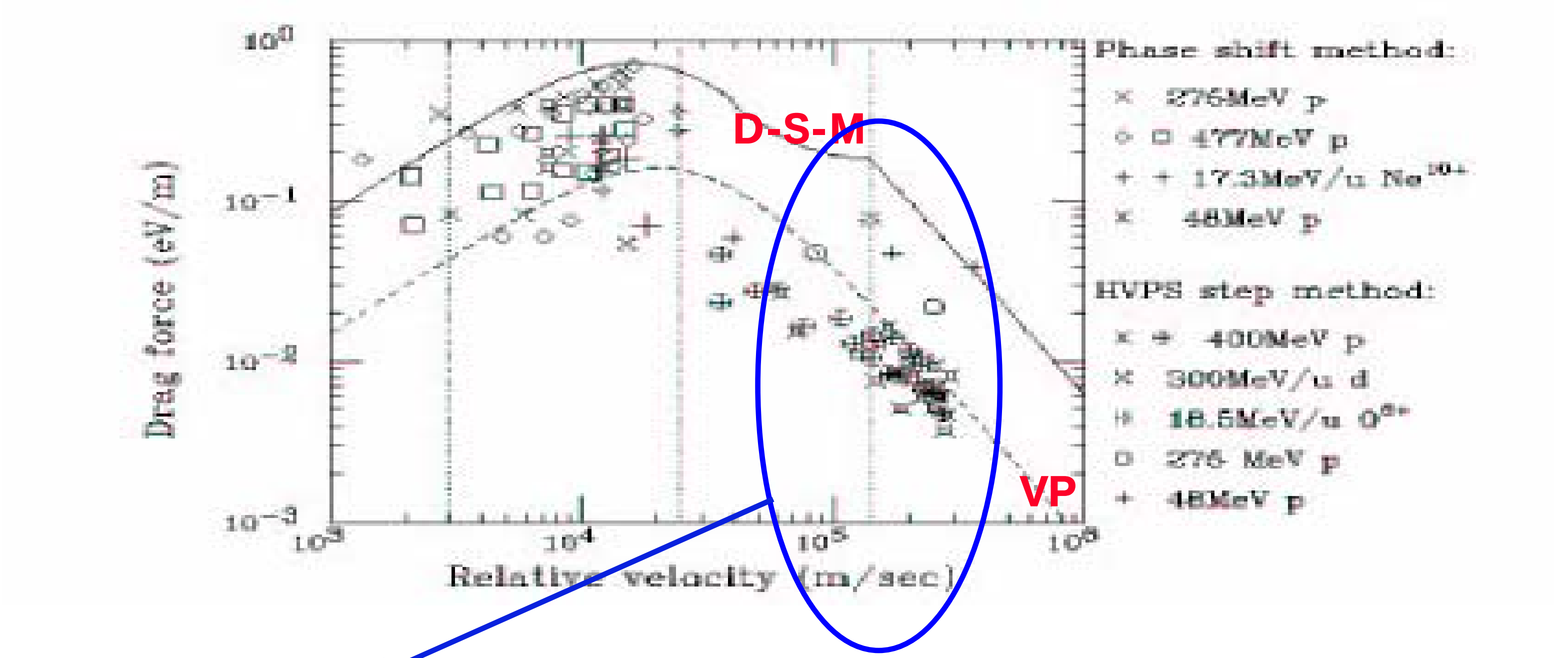
Task: We want to be sure that we are using the most appropriate magnetized cooling force formulas.

1. Infinite magnetic field formulas (D-S, D-S-M).
2. Empiric formula (VP) (any strength of field) – can show very different cooling dynamics for some parameters. Also, has different numerical factors.
3. Direct simulation/testing of formulas –

   GOAL: to have description of cooling force with about factor of 2 accuracy (or better).

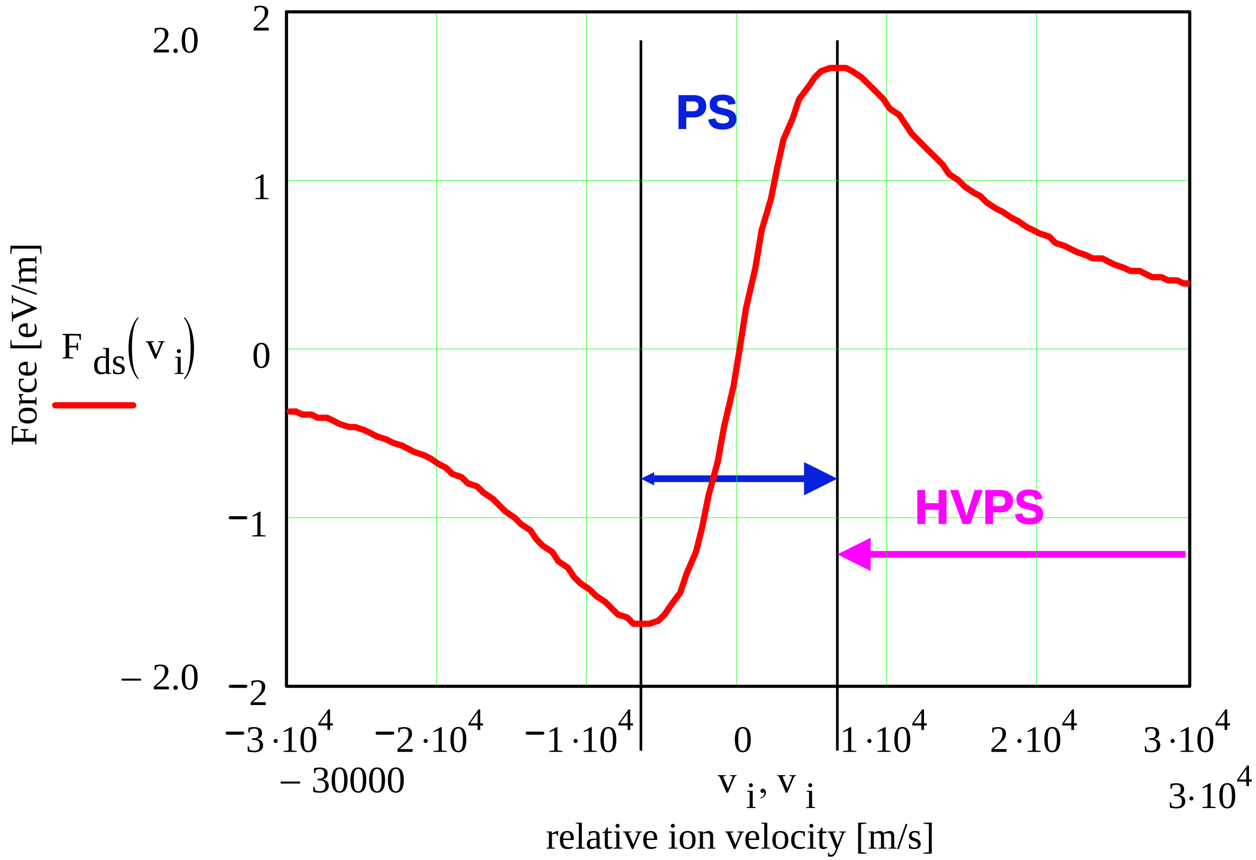
Comparison of D-S-M vs VP formulas in experiments (Longitudinal friction force)- 2001

Y-N. Rao et al.: CELSIUS, Sweden'2001:



Longitudinal: It looks like D-S-M overestimates cooling force by a factor of 10. VP agrees reasonably well.

Measurement methods: Phase Shift (PS) and Voltage Step (HVPS)



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Low relative velocities (linear part and maximum): Phase shift (PS) method

- The phase shift method is to apply both the electron cooling and the rf system (bunched ion beam):

measure the phase shift at equilibrium where the energy gain that an ion beam receives on passage through the rf cavity is equal to the energy loss during passage through the cooler

$$F_{\parallel} = \frac{Ze\hat{U}_{rf} \sin \Delta\phi_s}{L_c}$$

U_{rf} –the rf amplitude

$\Delta\phi_s$ –the equilbrium phase difference between the bunch and rf cavity

L_c - length of the cooler

Large relative velocities: HVPS method

- The electron beam energy is stepped by quickly changing the HVPS voltage:

The electron beam begins to drag the ion beam as a whole to a new energy corresponding to the new energy of electron beam. During this process the ion beam energy is tracked by recording its Schottky frequency shift

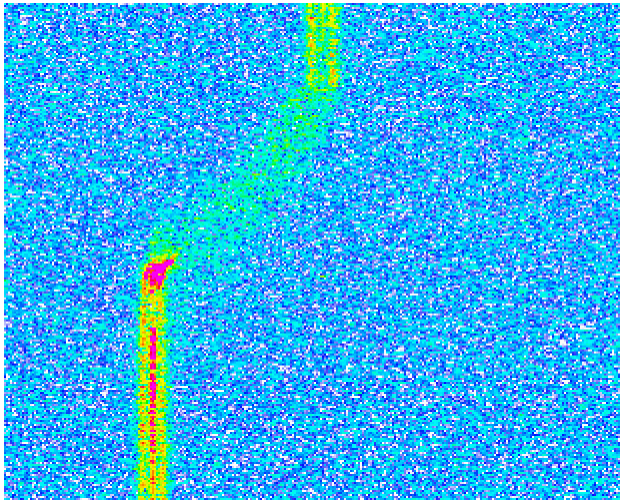
$$F_{\parallel} = \frac{1}{\eta_p} \frac{p_0}{f_0} \frac{\Delta f}{\Delta t} \cdot \frac{1}{\eta_{ec}}$$

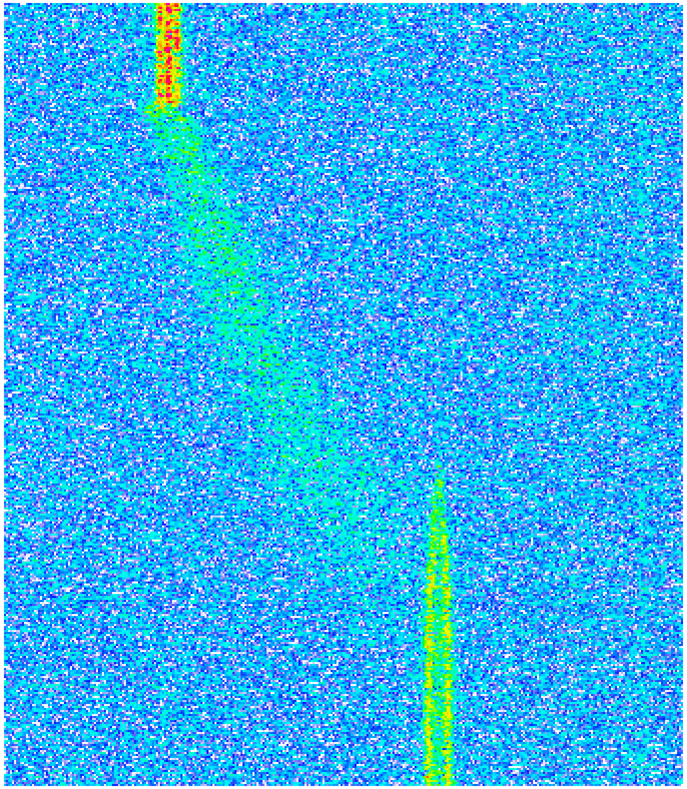
η_p – slippage factor, p_0 is ion momentum

η_{ec} – L_c/C – ration of cooler length to circumference

Δf – frequency shift recoded during time Δt

Accuracy of HVPS method –depends on "art of interpretation"





Accuracy of Phase Shift method: important since it allows to find location of the force maximum

1. One needs to introduce small velocity difference between electrons and ions – typically, voltage step is used to change energy of electrons.

2. One needs accurate measurement of the phase difference between the bunch and rf signal.

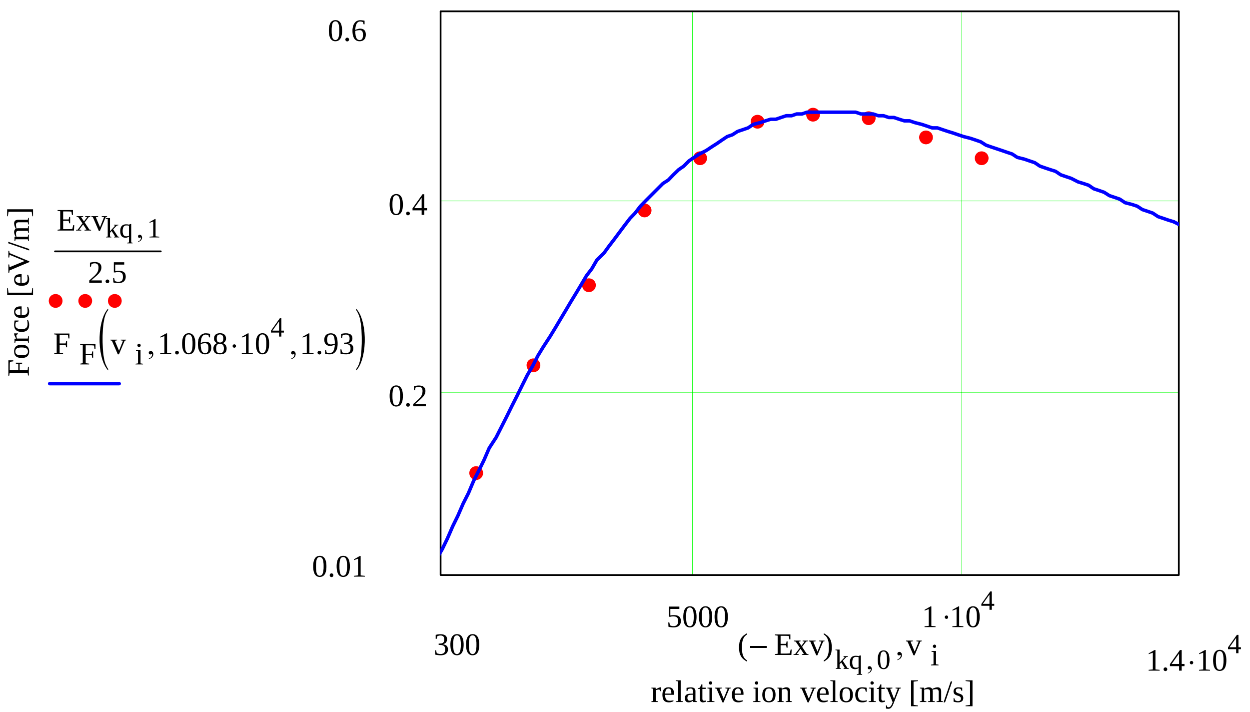
In our experiment at CELSIUS this measurement was improved by:

1. Changing rf frequency – allows very fine steps in velocity difference.

2. Instead of network analyzer without phase lock loop the phase was measured by phase discriminator.

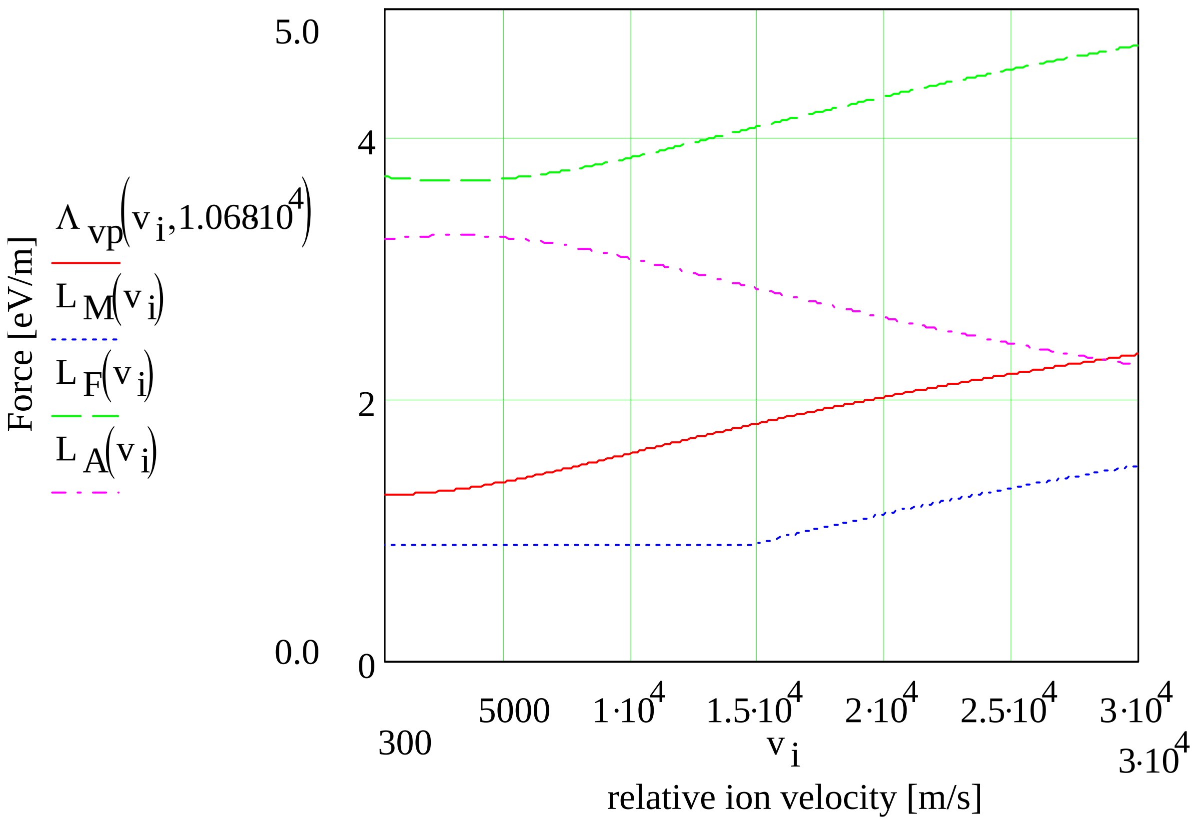
As a result, very accurate experimental data was obtained !

Fitting experimental data with VP formula assuming constant Coulomb logarithm



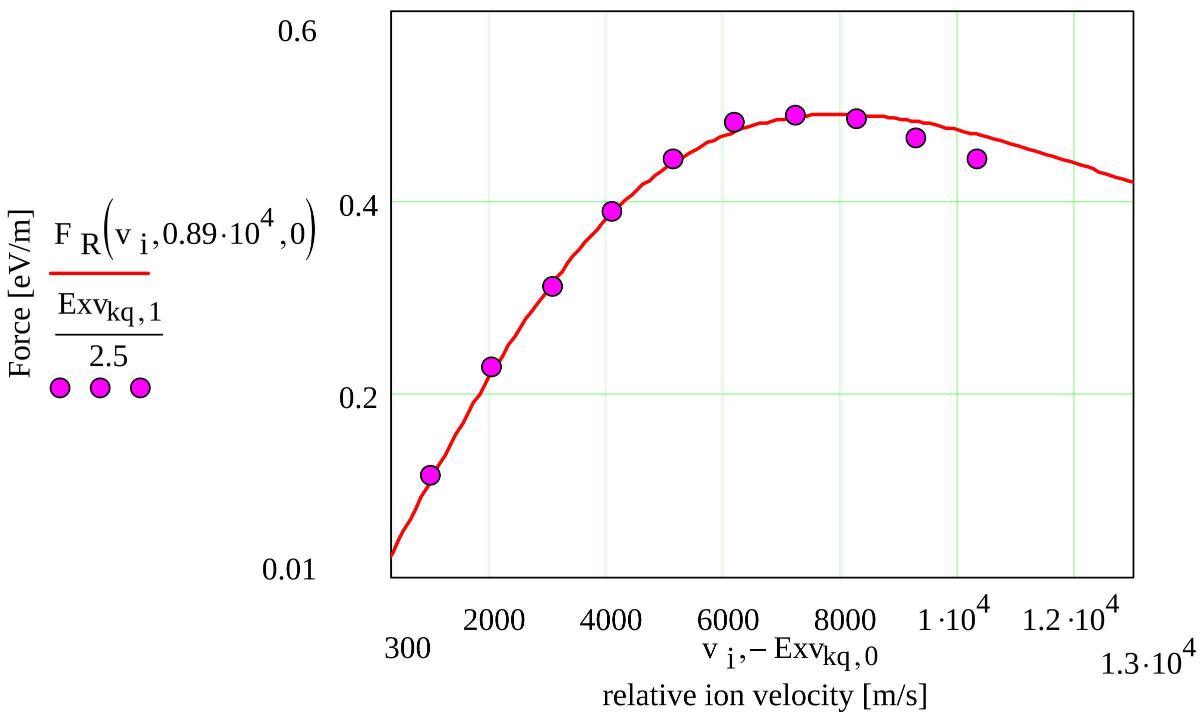
Found V_effective=1.068*10^4 m/sec

Coulomb logarithms in D-S-M (three logarithms L_M, L_F and L_A for three type of collisions) and in VP formulas (Λ_{VP})



Veff used in VP and D-S formulas was taken based on a fit with constant logarithm (few percent effect)

Fitting with VP Coulomb logarithm (including dependence on velocities)



Found V_effective=0.9*10^4 m/sec

Three types of collisions in magnetic field

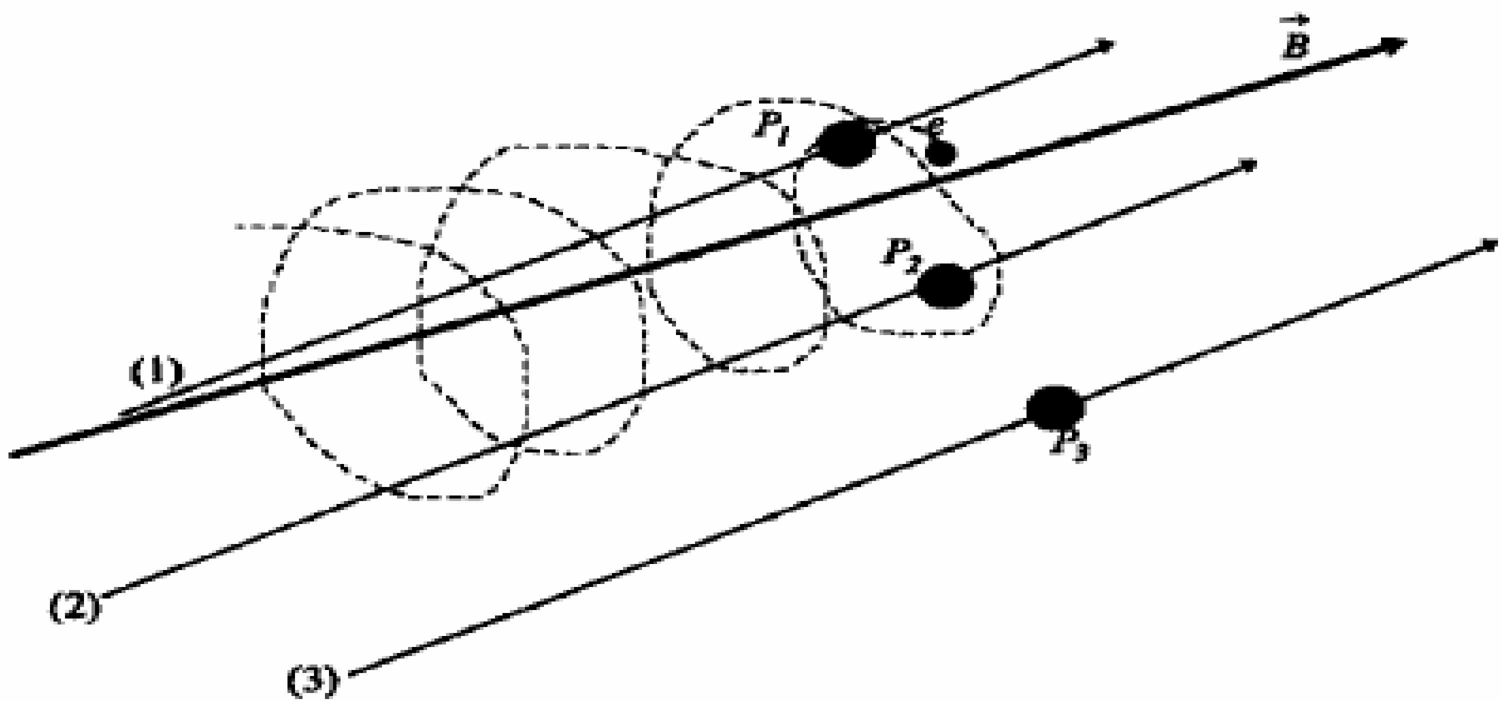


Fig. 3. Three kinds of collisions between an electron (e) and a particle (P) in a magnetized electron beam: fast (1), multiple (2) and "magnetized" (3).

Infinite magnetic field formulas Derbenev-Skrinsky (D-S) for collisions of "magnetized" type

dielectric approach (D-S) - analytic

$$F_{\parallel}^{A} = -\frac{3}{2}\omega_{pe}^{2}\frac{(Ze)^{2}}{4\pi\varepsilon_{0}}\left(\ln\left(\frac{\rho_{\max}^{A}}{\rho_{\min}^{A}}\right)\left(\frac{V_{\perp}}{V_{ion}}\right)^{2} + 2/3\right)\frac{V_{\parallel}}{V_{ion}^{3}}$$

$$F_{\perp}^{A} = -\frac{1}{2}\omega_{pe}^{2}\frac{(Ze)^{2}}{4\pi\varepsilon_{0}}\ln\left(\frac{\rho_{\max}^{A}}{\rho_{\min}^{A}}\right)\frac{\left(V_{\perp}^{2} - 2V_{\parallel}^{2}\right)}{V_{ion}^{2}}\frac{V_{\perp}}{V_{ion}^{3}}$$

$$\rho_{\max}^{A} = \min\left(r_{beam}, \rho_{\max}\right)$$

$$\rho_{\min}^{A} = \max\left(r_{L}, \rho_{\min}\right)$$

$$r_{L} = V_{\perp,RMS,e} / \Omega_{L}\left(B_{\parallel}\right)$$

Factor 2/3 without Ln offsets "defect" of adiabatic collisions by contributions with large impact parameters so that integral momentum transfer is no longer zero in long. direction when V_tr=0

Derbenev-Skrinsky-Meshkov (D-S-M) formulas with all three types of collisions included

$$F_{\|} = -\frac{2\pi n_e Z^2 e^4}{m} V_{\|}$$

$$\times \begin{cases} \frac{1}{V^3}\left(2L_{\mathrm{FH}} + \frac{3V_{\perp}^2}{V^2} L_{\mathrm{MH}} + 2\right), & \mathrm{H} \\ \frac{2}{\Delta_{\perp}^2 V_{\|}}\left(L_{\mathrm{FL}} + N_{\mathrm{L}} L_{\mathrm{AL}}\right) + \left(\frac{3V_{\perp}^2}{V^2} L_{\mathrm{ML}} + 2\right)\frac{1}{V^3}, & \mathrm{L} \\ \frac{2}{\Delta_{\perp}^2 \Delta_{\|}}\left(L_{\mathrm{FS}} + N_{\mathrm{S}} L_{\mathrm{AS}}\right) + \frac{L_{\mathrm{MS}}}{\Delta_{\|}^3}, & \mathrm{S} \end{cases}$$

$$L_{\mathrm{FH}} = \ln \frac{mV^3}{Ze^2 \omega_{\mathrm{B}}} = L_{\mathrm{FL}}\,,$$

$$L_{\mathrm{MH}} = \ln \frac{V\omega_{\mathrm{B}}}{2\Delta_\perp \omega_{\mathrm{e}}}\,,$$

$$L_{\mathrm{AL}} = \ln \frac{2\Delta_\perp}{V}\,,$$

$$L_{\mathrm{ML}} = \ln \frac{\max\left\{\dfrac{V}{\omega_{\mathrm{e}}}, \left(\dfrac{3Z}{n_{\mathrm{e}}}\right)^{1/3}\right\}}{2\rho_\perp}\,,$$

$$L_{\mathrm{FS}} = \ln \frac{m\Delta_\parallel \Delta_\perp^2}{Ze^2 \omega_{\mathrm{B}}}\,,$$

$$L_{\mathrm{AS}} = \ln \frac{2\Delta_\perp}{\Delta_\parallel}\,,$$

$$L_{\mathrm{MS}} = \ln\left(\frac{1}{2\rho_\perp}\left(\frac{3Z}{n_{\mathrm{e}}}\right)^{1/3}\right).$$

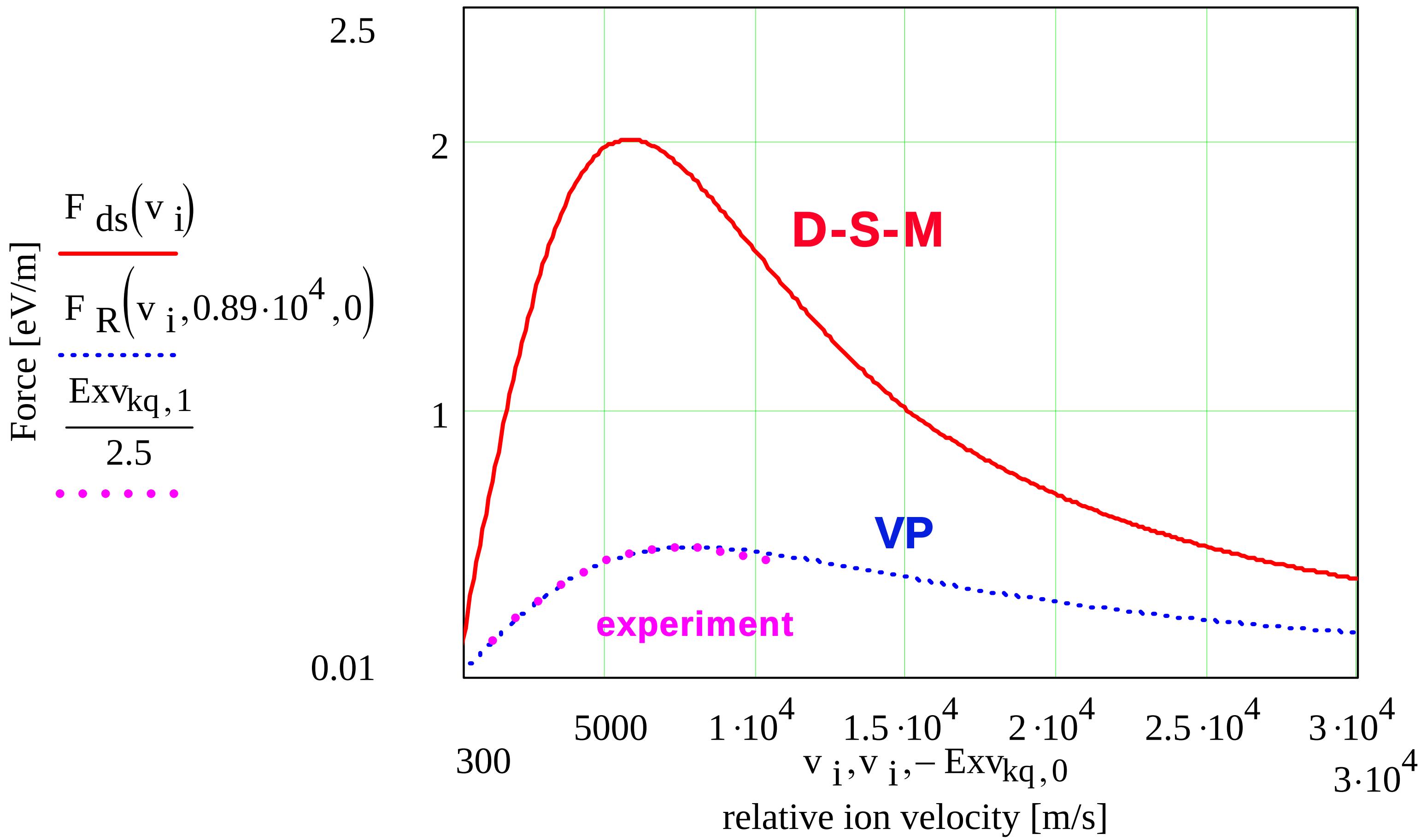
Coulomb logarithm for all three type of collisions in D-S-M formulas.

V. Parkhomchuk's (VP) empiric formula

empiric formula (VP)

$$\mathbf{F} = -\frac{1}{\pi}\omega_{pe}^{2}\frac{(Ze)^{2}}{4\pi\varepsilon_{0}}\ln\left(\frac{\rho_{\max}+\rho_{\min}+r_{L}}{\rho_{\min}+r_{L}}\right)\frac{\mathbf{V}_{ion}}{\left(V_{ion}^{2}+V_{eff}^{2}\right)^{3/2}}$$

D-S vs VP vs our experiment (December 2004) (θ=0, I_e=250mA)



What do we have ?

Based on December'04 experiments:

1. We can measure (measured for Ie=250mA and three angles) linear part and maximum of friction force with extremely good accuracy.

2. We can control V_effective and thus maximum of the friction force, making it bigger than:

   - longitudinal temperature of electron beam

   - effective angular spread given by magnetic field imperfections

We are therefore may be not sensitive to unknown parameters

What can we tell ?

1. We can test whether VORPAL code can reproduce experimental data and whether we can get numerically the friction force coefficient similar to experimental one.

2. We can see that experimental data, obtained during December experiment, is reasonably described by formulas, apart from numeric coefficient. However, we cannot make final statement about numerical factors in the formulas due to, for example, possible non-linear dependence on electron beam current (expected for these parameter).

   Similar measurements should be repeated for several values of electron current, several values of tilt angles in both planes, various values of magnetic field.

Needed experiments

A. Longitudinal friction force:

1. (θ=0) measure linear part of the force going from one unstable point to another (back and forth) with 5-10 Hz steps in frequency for several values of electron current: 20, 50, 100, 250, 500 mA

Time: if manually, each loop/one current swipe will take at least one hour - VZ will set up a script to do it automatically.

2. Horizontal tilts: 0, 0.2 mrad, 0.4 mrad, 0.8, 1.5 mrad, repeat with 250mA

3. Vertical tilts: 0, 0.2, 0.4, 0.8, 1.5, repeat with 250 mA

Needed time: 1-2 shifts

Dependence on magnetic field

4. Dependence on magnetic field: both to establish validity of formulas and test regimes relevant for high-energy cooling.

4.1. Bad magnetization. I=1A.
Do measurements at 3 values of B=0.03, B=0.06, B=0.12 (or any other values with B=0.12 and less).

4.2. Transition: I=0.5A, B=0.05, B=0.1, B=0.15

4.3. Good magnetization: I=0.1A, B=0.5, B=0.1, B=0.15

Time needed: 2 shifts, provided that cooler is working good for magnetic field values different from standard one. Testing and establishing working values for magnetic field prior to experiments is needed.

Longitudinal friction force measurements

To complete basic longitudinal friction force measurements

will request 1 week (with 3-4 shifts).

If successful – this data should be sufficient to come up with definite conclusions about numeric coefficient in formulas.

Other measurements: transverse cooling, Z scaling, etc.

- Other experiments are possible such as:

B. Transverse Cooling and IBS:

....

C. Transverse cooling rates:

....

D. Z scaling, testing RHIC regime – very important

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will need to make priorities

Will need probably one more week (with request for 3 shifts). Also, if found necessary, some measurements from previous set on longitudinal force can be repeated/improved.